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GUIDANCE ANALYSIS OF AERODYNAMIC PHASE OF DESCENT TO THE SURFACE OF MARS

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SUMMARY

The trajectory of a spacecraft that descends through the atmosphere to a soft landing on the surface of Mars can be divided into two portions which depend upon the forces that affect the spacecraft. The motion of the spacecraft is governed by gravitational and aerodynamic forces during the first portion of the trajectory; it is governed by propulsion or drag devices or both during the second portion of the trajectory in order to achieve a soft landing. The performance of a spacecraft with a L/D ratio of 0.5 and a ballistic coefficient of 120 psf was studied. Only the first portion of the descent within the atmosphere was considered. The results indicate that the depth of the entry corridor is ample only if an accurate model of the atmosphere is available. In almost all cases, the velocity of the spacecraft will be greater than 2000 fps when the altitude has decreased to 30 000 feet. The feasibility should be considered of drag devices being used to decrease the velocity to a lower value because the size of the propulsion system will be influenced significantly by the velocity at the beginning of the powered phase.

INTRODUCTION

The tenuous atmosphere of Mars requires that the descent of a manned spacecraft to the surface of the planet combine characteristics of the atmospheric entry at Earth and the lunar landing trajectory. The aerodynamic forces are used to decelerate the spacecraft and to guide the spacecraft to the target area. The propulsion system is used to achieve a soft landing at an acceptable location. It is very important that the velocity and distance from the target be minimized at the end of the aerodynamic portion of the trajectory so that the size of the required propulsion system will be minimized.

A study was made of the first portion of the descent trajectory to determine the required performance of the propulsion system. The landing spacecraft discussed in reference 1 and the guidance method presented in reference 2 were used in the study. The spacecraft has an L/D ratio of 0.5 and a ballistic coefficient of 120 psf; the only method of control is to roll the spacecraft. The guidance method attempts to steer the spacecraft along a reference trajectory which is computed onboard shortly before the entry begins. This method requires a minimum of predetermined gains or constants. The results of the study are contained in this report.

SYMBOLS

a	acceleration, ft/sec^2
C_D	drag coefficient
g	acceleration caused by gravitational attraction at surface of earth, ft/sec^2
h	altitude, ft, n. mi.
K_{oc}	overcontrol parameter
K_1, K_2, K_3	influence coefficients
L/D	lift-to-drag ratio
q	dynamic pressure, psf
R	range, deg or radian
S	reference area, ft^2
t	time, sec
V	velocity, fps
W	weight, lb
γ	flight-path angle, deg or radian
ΔR	error in range at 30 000-ft altitude, n. mi.
ΔV	velocity increment, fps

δD	error in drag acceleration, ft/sec^2
δR	error in range, n. mi.
δV	error in velocity, fps
ζ	cross range, deg or radian
η	true anomaly, deg or radian
ϕ	roll angle, deg or radian

Subscripts:

a	apoapsis
com	command
en	entry
f	final
max	maximum
nom	nominal
p	periapsis
T	target
o	surface

METHOD

The sequence of maneuvers which occurs during the descent to the surface is shown in figure 1. Initially, the spacecraft is in a parking orbit with arbitrary values for the orbital elements. The descent is begun by a decrease in the velocity of the spacecraft when it is at the apoapsis of the parking orbit. The magnitude of the velocity change is determined by the desired value of the periapsis altitude of the descent orbit. The apoapsis and periapsis altitudes of the descent orbit determine the true anomaly (η_{en}), the velocity (V_{en}), and the flight-path angle (γ_{en}) of the spacecraft when it reaches the edge of the effective atmosphere. The location of the target is specified by the angle between the periapsis vector and the projection of the target vector into the plane of the descent orbit (η_T) and by the angle between the target vector and the plane of the descent orbit (ζ_T). The first angle will be called the range from periapsis, and the second angle will be called the cross range.

Entry guidance methods similar to those of reference 2 are discussed in references 3 and 4. For all three methods, the measured deviations from a nominal trajectory are used to guide the spacecraft to the target. Normally, the region of validity of the guidance method is limited to the linear neighborhood of the nominal trajectory, but there are various schemes designed to increase the region of validity.

The drag acceleration and the range to the target are used as control parameters in all three methods. The third control parameter can be the flight-path angle (ref. 2), the altitude (ref. 3), the altitude rate (ref. 4), or any other applicable parameter. The flight-path angle and the altitude rate are equivalent because they can be related by the velocity of the spacecraft. Either of these parameters is known more accurately than the altitude and, therefore, are better choices for the third control parameter.

The method used to increase the region of validity does not depend upon the choice for the third control parameter. The region of validity can be increased by the use of a single constant overcontrol parameter (ref. 3) or by the use of empirically determined variable weighting factors (ref. 4). The region of validity also may be increased by the use of a variable nominal trajectory (ref. 2). The latter method is the one which was used for this study.

The variable nominal trajectory method requires that the calculations of the nominal trajectory and the influence coefficients be performed immediately prior to entry. The roll angle of the spacecraft is held constant, and the entry trajectory is determined by integration of simplified equations of motion. The roll angle is changed, and the integration is repeated until the proper range is obtained. Then the adjoint set of perturbation equations are integrated backwards along the nominal trajectory to obtain the influence coefficients. The reference values of the control parameters and the values of the influence coefficients are stored as functions of the velocity. The control law used for guidance is the following.

$$\phi_{com} = \cos^{-1}\left\{\left(\frac{L}{D}\right)_{nom} \Big/ \left(\frac{L}{D}\right)_{max} + K_{oc}\left[K_1(\gamma_{nom} - \gamma) + K_2(D_{nom} - D) + K_3(R_{nom} - R)\right] \Big/ \left(\frac{L}{D}\right)_{max}\right\}$$

where K_1, K_2, and K_3 are the influence coefficients and where K_{oc} is the overcontrol parameter introduced in reference 3.

The major advantage of the variable nominal trajectory method is its flexibility. Not only can the same guidance program handle a wide range of entry conditions and target locations, but also properties of the spacecraft and of the planet need not be known until shortly before the entry is begun.

NUMERICAL APPLICATIONS AND RESULTS

The four-degree-of-freedom digital trajectory program discussed in reference 5 was used to obtain the results presented in this report. The nominal characteristics of the spacecraft were also taken from reference 5 and were as follows.

L/D	0.5
W/C_DS, psf	120
Maximum roll rate, deg/sec	±20
Roll acceleration, deg/sec^2	±10
Roll deadband, deg	± 4

The control system characteristics are those of the Apollo command module. The models of the Martian atmosphere proposed in reference 6 were used for the study.

The apoapsis altitude of the descent orbit was assumed to be 10 000 n. mi. for all cases, and the edge of the effective atmosphere was assumed to occur at an altitude of 300 000 feet (49.4 n. mi.). The inertial velocity, flight-path angle, and true anomaly of the spacecraft at the beginning of entry are presented in figure 2 as functions of the periapsis altitude. Although the periapsis altitude varies between -100 n. mi. and 49.4 n. mi., the region of practical interest is between -20 n. mi. and 40 n. mi. The region of interest for the flight-path angle is between -10.1° and -3.7°; and for the true anomaly, between -24.0° and -8.9°. The inertial velocity varies between 15 077 and 15 082 fps.

The altitude, relative velocity, and acceleration for a typical entry trajectory are shown in figure 3 as functions of time. The target was located in the plane of the descent orbit and 20° beyond the periapsis point. The periapsis altitude was 10 n. mi., and the mean density atmosphere was assumed. The inertial velocity at the beginning of entry was 15 078.3 fps, and the flight-path angle was -9.35°. The total range traveled within the atmosphere was 42°. The altitude of the spacecraft decreased to a minimum of 93 000 feet before it increased to a maximum of 192 000 feet at 425 seconds after the beginning of entry. The maximum acceleration was 3.88g during the first portion of the entry and was 2.06g during the second portion of the entry. The trajectory was assumed to end when the altitude became less than 30 000 feet. At this time, the relative velocity of the spacecraft was 3050 fps, and the spacecraft was 15.4 n. mi. from the target.

The depth and location of the entry corridor are determined by variation of the periapsis altitude while the remaining variables are kept fixed. In figure 4, the low density atmosphere was used, and the target was located 10° beyond the periapsis point and in the plane of the descent orbit. The effects are shown of variations in the periapsis altitude upon the relative velocity of the spacecraft and upon the distance from the target at the end of the trajectory (fig. 4). The miss distance is less than 25 n. mi. if the periapsis altitude is between -18 n. mi. and 20 n. mi. If the periapsis altitude is outside of this range, which will be defined as the entry corridor, the miss distance increases sharply. The final velocity is 2680 fps at the bottom of the corridor and increases as the periapsis altitude is increased. The final velocity increases to 8050 fps at the top of the corridor.

Some of the characteristics of trajectories within the entry corridor are summarized in figure 5. The limits of the entry corridor, the maximum acceleration, the maximum dynamic pressure, and the relative velocity at an altitude of 30 000 feet are presented as functions of the locations of the target for each atmospheric model. The depth of the entry corridor is affected slightly by different atmospheric models; the location of the corridor is raised as the density is increased. The depth of the corridor is from 34 n. mi. to 40 n. mi. when the target is located 10° beyond the periapsis. The depth of the corridor decreases to between 13 n. mi. and 16 n. mi. as the distance to the target is increased to 40° beyond the periapsis. The depth of the corridor is ample if the correct atmospheric model is known before the nominal periapsis altitude is selected. The opposite is true if the low and high density atmospheres represent the extremes which can be expected. In this case, the real corridor is bounded by the top of the corridor for the low density atmosphere and by the bottom of the corridor for the high density atmosphere. The depth of the corridor is 25 n. mi. when the target is 10° beyond the periapsis. The corridor depth decreases to 20 n. mi. when the distance to the target is increased 4° and completely disappears if the target is 37.5° beyond the periapsis. Therefore, it is extremely important that an accurate model of the atmosphere be available before the descent maneuver is begun.

The maximum acceleration of 3.75g and the maximum dynamic pressure of 405 psf are achieved when the shortest range and the low density atmosphere are used. The minimum relative velocity at an altitude of 30 000 feet is 1700 fps. This velocity occurs at the bottom of the corridor for the high density atmosphere and for the shortest range. The maximum relative velocity is 8000 fps and occurs at the top of the corridor for the low density atmosphere and for the shortest range. The relative velocity at 30 000 feet can be reduced to below 6000 fps if the top of the corridor is lowered approximately 5 n. mi. when the target is located 10° beyond the periapsis. The final velocity will be less than 6000 fps throughout the corridor if the target is located at least 20° from the periapsis. While the periapsis was within the corridor, the spacecraft did not miss the target by more than 30 n. mi.; in most cases, the miss distance was less than 15 n. mi. For all cases within the corridor, the minimum altitude during the first phase of the entry was greater than 50 000 feet.

Although the purpose of the study was not to determine the landing footprint of the spacecraft, it was of interest to obtain an estimate of the cross-range capability of the spacecraft. The mean density model of the atmosphere was used, and an angle η_T of 20° was assumed. It was found that the spacecraft could be guided to a target which was within 4° of the plane of the descent orbit.

CONCLUDING REMARKS

Although the atmosphere of Mars is much rarer than the Earth atmosphere, aerodynamic forces still dominate the motion of a spacecraft during a descent to the surface of Mars. The effect of the decreased density is most apparent near the end of the descent when the velocity of the spacecraft is greater than it would be for a descent to Earth. In all cases, the velocity of the spacecraft at an altitude of 30 000 feet is greater than 1700 fps. The maximum dynamic pressure is 405 psf, and the maximum acceleration is 3.75g.

This study indicates a need to consider the use of drag devices such as parachutes to decrease the final velocity of the spacecraft. The use of drag devices could decrease significantly the size of the propulsion system for landing.

The depth of the entry corridor is sufficient only if an accurate model of the atmosphere is known before the spacecraft leaves the parking orbit. One of the advantages of the mission proposed in reference 1 is the long time spent in orbit around Mars before the soft landing is attempted. Part of this time can be used to improve the knowledge of the atmosphere of Mars.

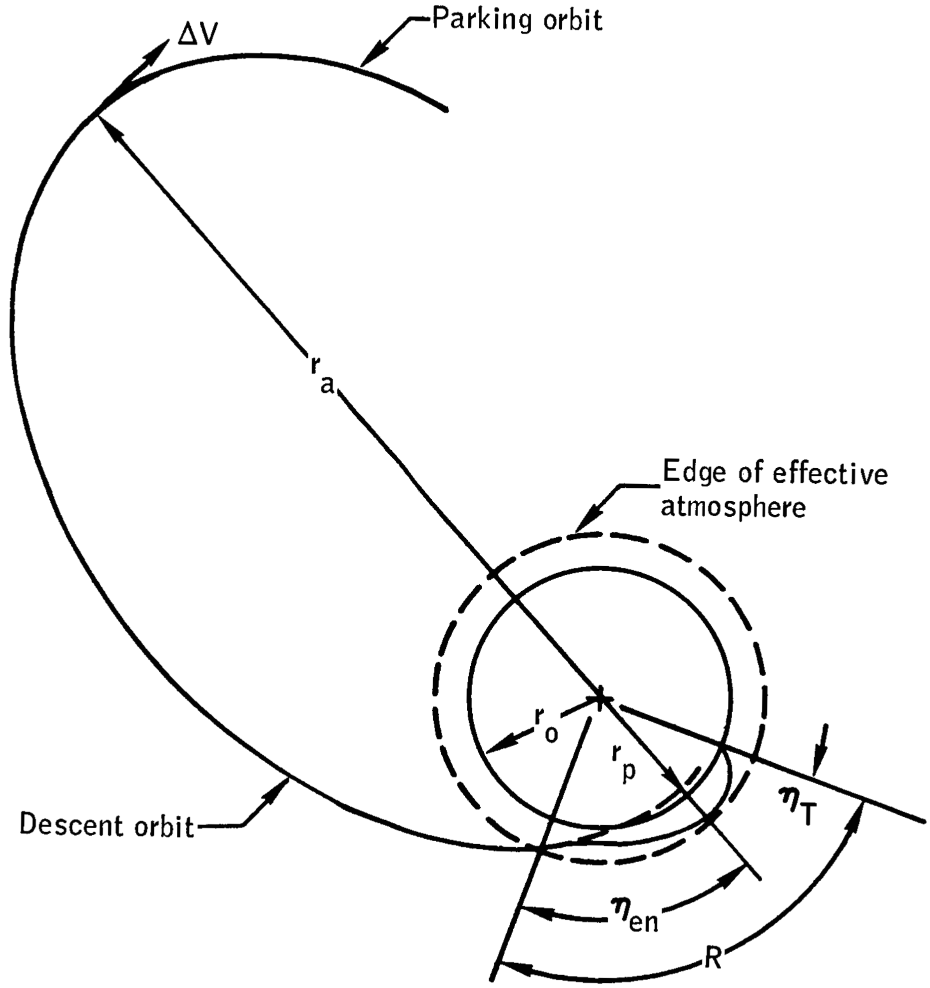

Figure 1.- Description of descent maneuver.

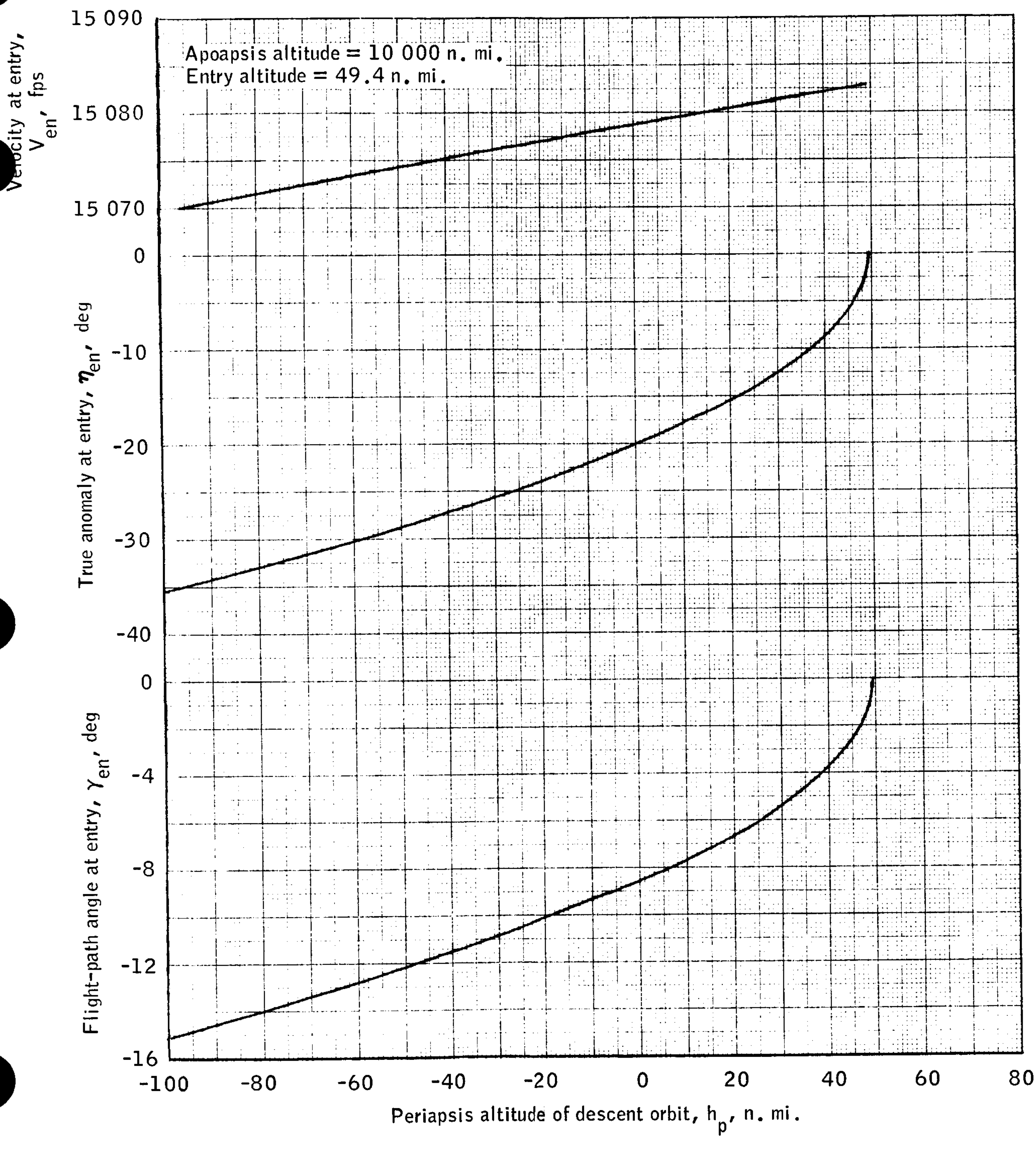

Figure 2.- Effect of periapsis altitude on entry conditions.

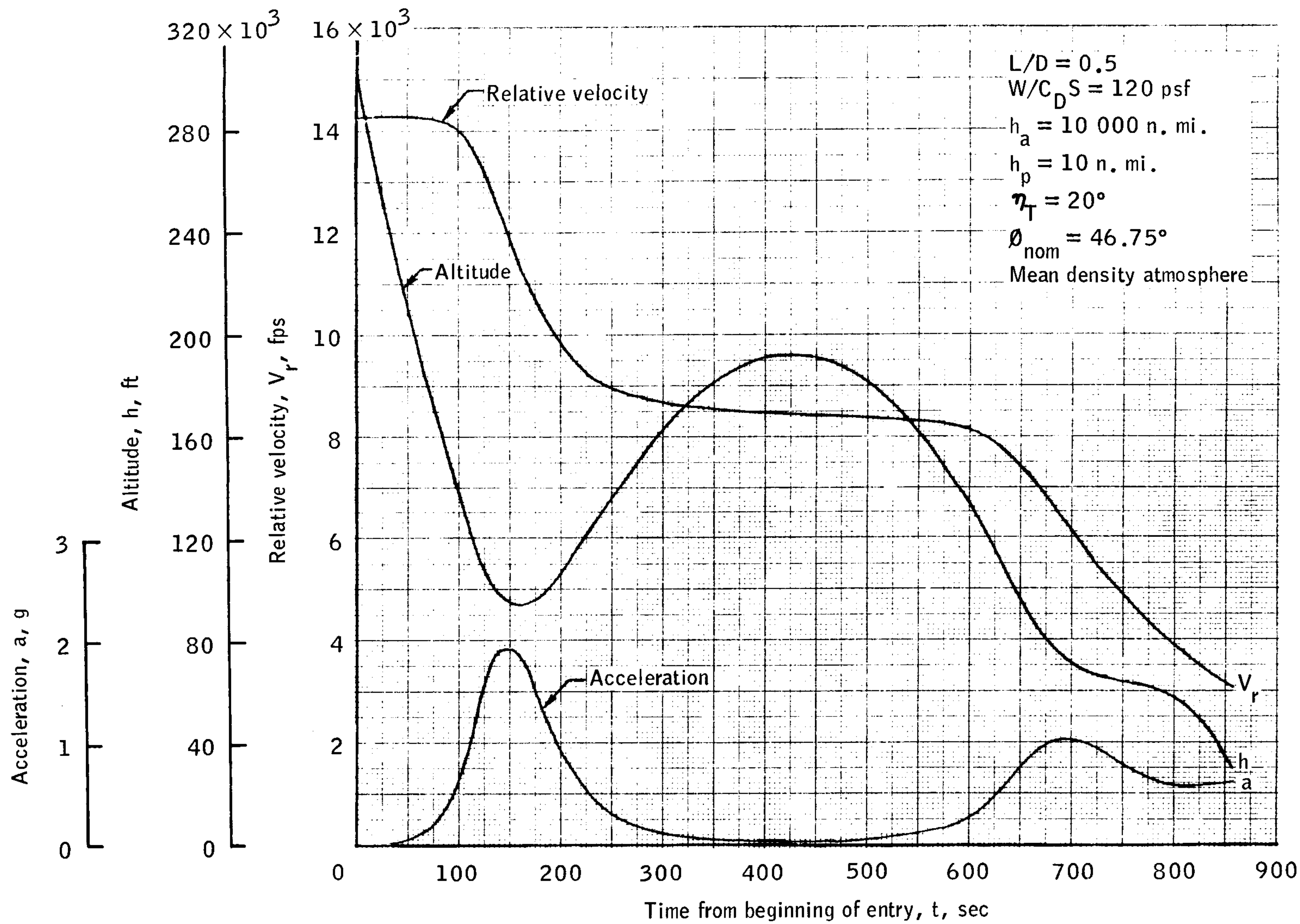

Figure 3.- Time history of altitude, relative velocity, and acceleration of typical descent trajectory.

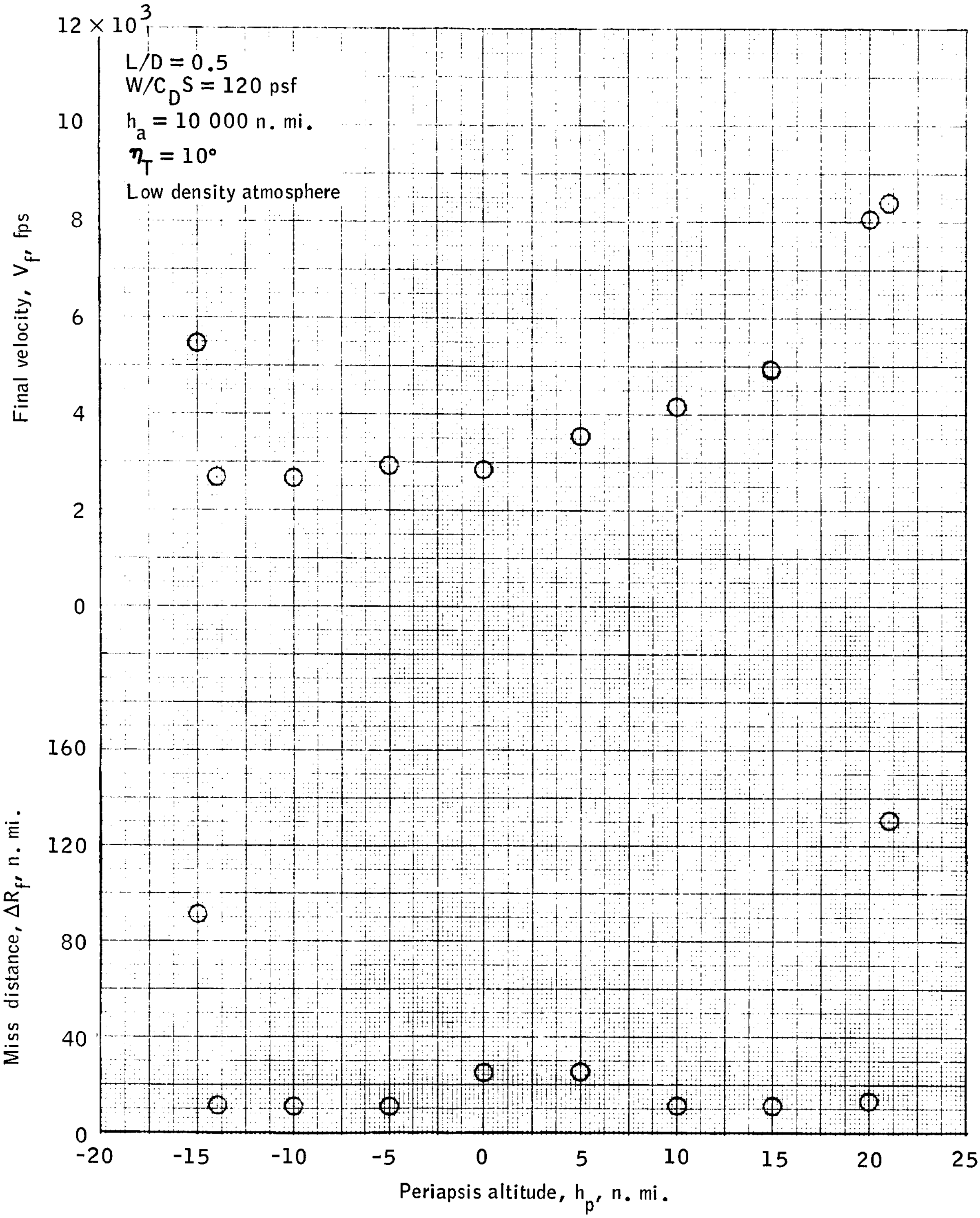

Figure 4.- Miss distance and final velocity across corridor for typical location of target and low density atmosphere.

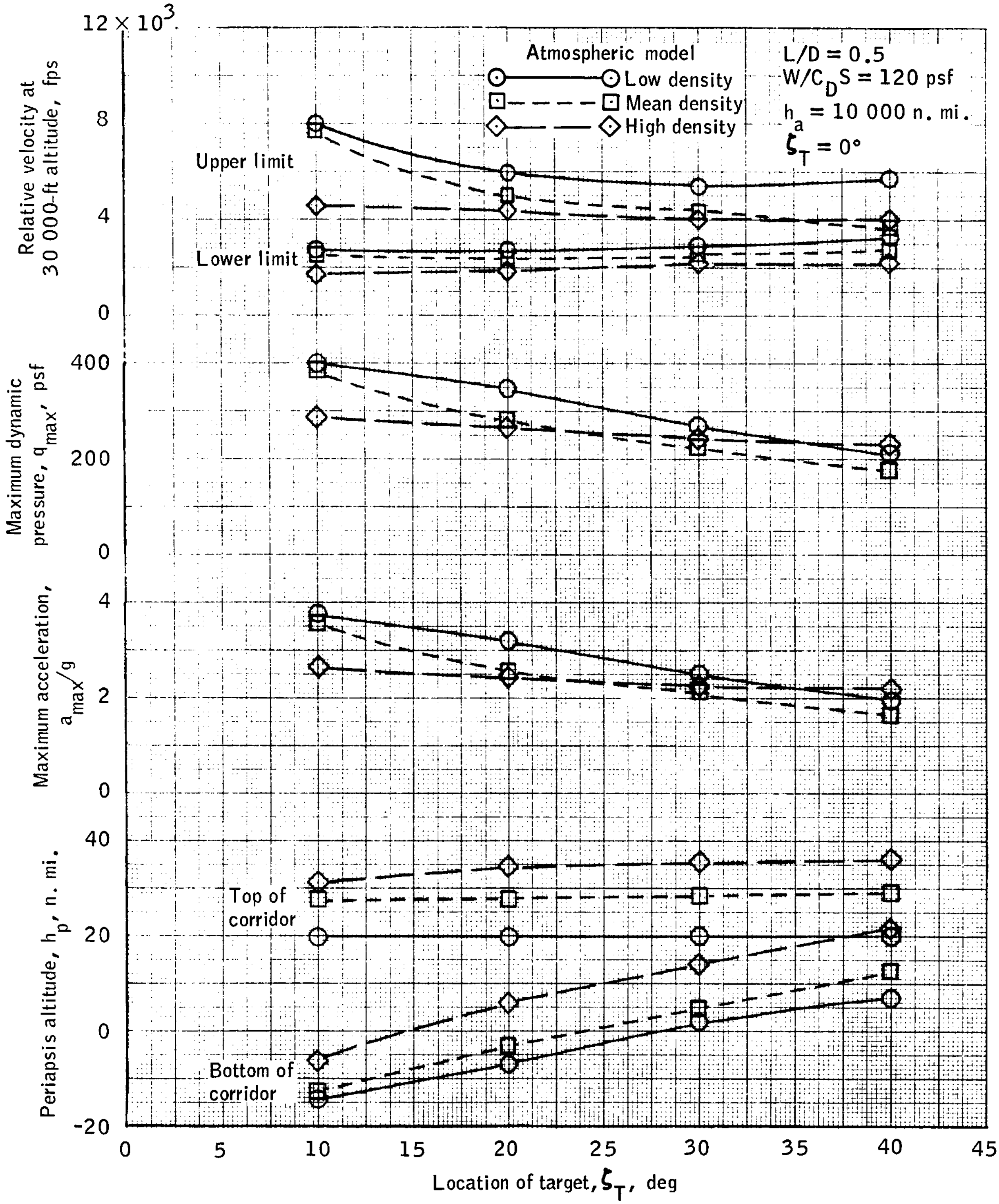

Figure 5.- Summary of conditions within entry corridor for targets located between 10° and 40° beyond the periapsis of the descent orbit.

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